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VENTILATION INVOLVED IN THE USE OF GASOLINE-POWERED EQUIPMENT IN ENCLOSED SPACES (NOT IN MINES OR TUNNELS)

BY

L. B. BERGER

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UNITED STATES DEPARTMENT OF THE INTERIOR - BUREAU OF MINES

VENTILATION INVOLVED IN THE USE OF GASOLINE-POWERED EQUIPMENT IN ENCLOSED SPACES (NOT IN MINES OR TUNNELS)[1]

By L. B. Berger[2]

INTRODUCTION

The use of gasoline engines as the motive power for lift trucks, tractors, and other types of mobile equipment operated in enclosed spaces, such as industrial plants and warehouses, may create a hazard because of the carbon monoxide present in the exhaust gases of the engines; gasoline-powered equipment should not be used in mines or tunnels. Because the equipment is mobile, local ventilation usually is impracticable, and general ventilation of the spaces is necessary to dilute and remove the carbon monoxide. To estimate the rate of ventilation required in such situations, information is necessary on the concentration of carbon monoxide in the exhaust gas and the rate at which exhaust gas is produced under given operating conditions. The purpose of this paper is to present data that may be used in making estimates of ventilation requirements.

COMPOSITION OF GASOLINE-ENGINE EXHAUST GAS

The exhaust gas of a gasoline engine consists mainly of carbon dioxide, carbon monoxide, hydrogen, oxygen, and unburned hydrocarbons (usually reported as methane), together with the nitrogen present as a residue from the air supplied for combustion.[3] The exhaust also contains water vapor resulting from combustion of the hydrogen of the fuel. The water-vapor content is not included in exhaust-gas analyses calculated on a "dry" basis and is not involved in the estimation of ventilation requirements.

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[1] The Bureau of Mines will welcome reprinting of this paper, provided the following footnote acknowledgment is used: "Reprinted from Bureau of Mines Inf. Circ. 7404."

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[3] In addition to these major constituents, the exhaust may contain low concentrations of aldehydes, oxides of nitrogen, oxides of sulfur (if the fuel contains sulfur), soot, and possibly traces of unsaturated hydrocarbons. Some of these materials may have their source in the "cracking" or partial oxidation of lubricating oil present in the combustion space of the engine. The toxic properties of these materials usually may be disregarded in ventilation estimates, because if enough ventilation is supplied to dilute the carbon monoxide content of the exhaust to an acceptable level, the concentrations of these minor constituents of the exhaust become negligible in the resulting atmosphere.

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The proportions of these various gases (particularly products of combustion such as carbon dioxide, carbon monoxide, and hydrogen) present in the exhaust depend on the proportions of fuel and air in the mixture supplied to the engine by the carburetting device, or, in other words, on the "fuel:air ratio" at which the engine is operated. Fuel:air ratio usually is expressed on a weight basis - that is, pound of fuel per pound of air. To obtain representative data showing the relation of exhaust-gas composition to fuel:air ratio, a number of published analyses[4/], [5/], [6/], [7/], [8/] of gasoline-engine exhaust gas have been combined and averaged, with the results given in table 1 and figure 1.

There are some minor disagreements in the data cited that may be due to slight differences in fuel composition, to the effect of probable analytical errors, and possibly to the effect of different engine designs. It is believed, however, that the "average" curves shown in figure 1 are sufficiently representative to be applied satisfactorily in making estimates of ventilation requirements.

It may be noted in figure 1 that a fuel:air ratio of 0.067 is designated as the "chemically correct" fuel:air ratio, meaning that fuel and air are present in such proportions that, theoretically, there is just enough air in the mixture to burn all of the carbon in the fuel to carbon dioxide and all of the hydrogen in the fuel to water vapor. Actually, however, this ideal condition is not realized, and, as shown in figure 1, measurable quantities of carbon monoxide and hygroden (products of incomplete combustion) are present in the exhaust gas even at fuel:air ratios less than the chemically correct one, or, in other words, at fuel:air ratios at which excess air is present in the mixture supplied to the engine, and in the exhaust gas.

The presence of excess air in the mixture is evidenced by the marked upswing of the oxygen curve at fuel:air ratios less than that which is chemically correct. Free oxygen in the exhaust reaches a minimum near the chemically correct mixture and remains constant at about 0.3 percent on through the highest fuel:air ratio shown. Mixtures containing excess air, as represented by fuel:air ratios less than that which is chemically correct, are designated as "lean" mixtures, and mixtures in which there is not enough air for complete combustion of the fuel, as represented by fuel:air ratios greater than the chemically correct, are known as "rich" mixtures. It is evident that the proportion of products of

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4/ Jones, G. W., and Fieldner, A. C., Gasoline Saved on Government Trucks by Adjusting Carburetors by Gas Analysis: Bureau of Mines Rept. of Investigations 2487, 1923, 13 pp.

5/ Sayers, R. R., Fieldner, A. C., Yant, W. P., and Thomas, B. G. H., Experimental Studies on the Effect of Ethyl Gasoline and Its Combustion Products: Bureau of Mines Monograph 2, 1927, 447 pp.

6/ Graf, S. H., Gleeson, G. W., and Paul, W. H., Interpretation of Exhaust Gas Analyses: Bull. Ser. No. 4, Oregon State Agricultural College Engineering Experiment Station, 1934, 49 pp.

7/ D'Alleva, B. A., and Lovell, W. G., Relation of Exhaust Gas Composition to Air:Fuel Ratio: Soc. Auto. Eng. Jour., vol. 38, 1936, pp. 90-96.

8/ Gerrish, H. C., and Voss, F., Interrelation of Exhaust-Gas Constituents: Nat. Adv. Comm. Aeronautics Rept. No. 616, 1937, 8 pp.

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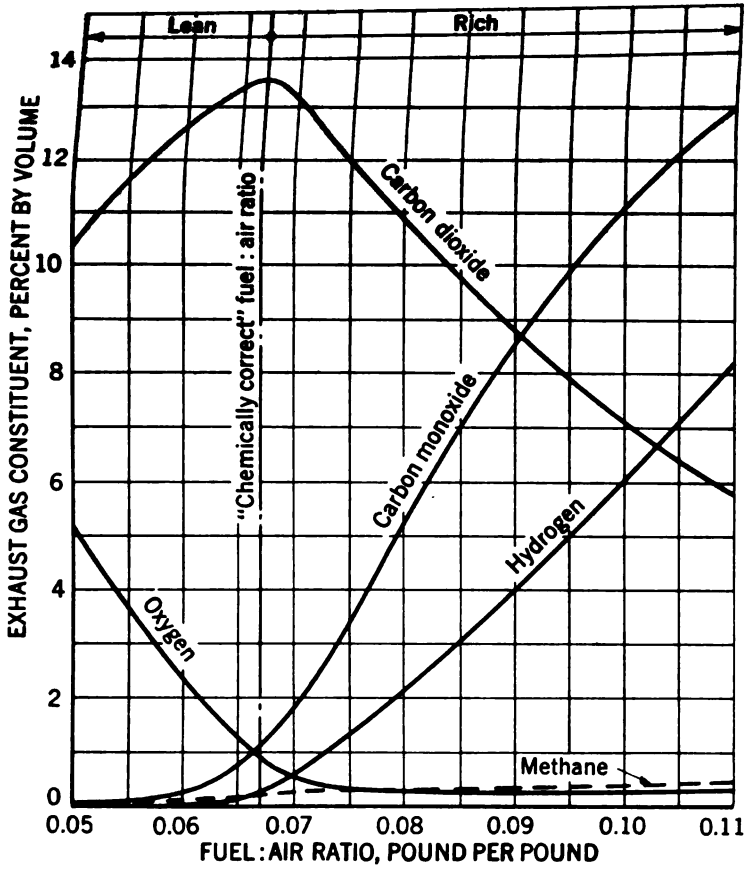

Figure 1.—Relation of composition of gasoline engine exhaust gas to fuel : air ratio.

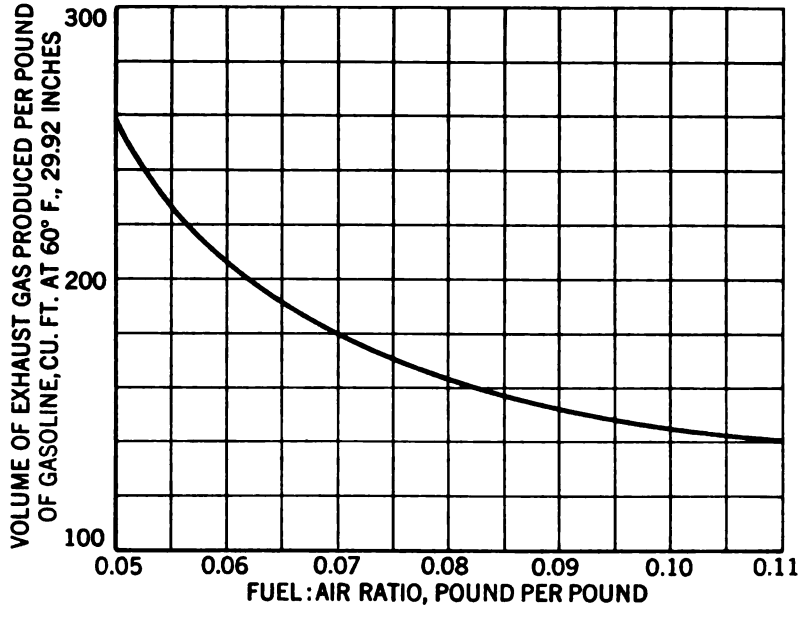

Figure 2.—Relation between fuel ; air ratio and volume of exhaust gas produced per pound of gasoline.

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incomplete combustion - carbon monoxide and hydrogen - increase progressively as the proportion of air in the mixture is reduced at increasing fuel:air ratios on the rich side.

TABLE 1. - Average composition of gasoline engine exhaust gas at different fuel:air ratios (compiled from various published data)

Fuel:air ratio, pound of fuel per pound of air	Composition of exhaust gas, percent by volume[1]					
	Carbon dioxide	Oxygen	Carbon monoxide	Hydrogen	Methane	Nitrogen[3]
0.05	10.36	5.10	0.05	0.02	0.07	84.40
.06	12.56	2.35	.20	.05	.10	84.74
.067	2/13.51	-	-	-	-	-
.07	13.14	0.50	1.74	0.60	0.30	83.72
.08	10.84	.28	5.16	2.18	.30	81.24
.09	8.76	.23	8.50	4.03	.37	78.11
.10	7.08	.30	11.00	5.97	.35	75.30
.11	5.75	.30	12.95	8.20	.50	72.30

1/ On a dry basis; water vapor formed by combustion of the hydrogen of the fuel not included.
2/ Maximum carbon dioxide occurs at fuel:air ratio of 0.067.
3/ Nitrogen by difference: (100 - sum of average percentages of other constituents of exhaust gas).

The concentration of carbon dioxide in the exhaust gas reaches a maximum approximately at the chemically correct fuel:air ratio, decreasing on the lean side from this peak because of dilution with excess air, and decreasing on the rich side because an increasing proportion of the carbon in the fuel is burned to carbon monoxide as fuel:air ratio increases.

The data given in table 1 and figure 1 cover the range of fuel:air ratios within which gasoline engines usually operate, although to obtain satisfactory performance most engines are supplied with fuel:air mixtures on the rich side of the chemically correct ratio. Also, the fuel:air ratio of the mixture supplied to an engine by the carburetor may vary considerably throughout the power-output range of the engine. The mixture supplied to an engine at idling speed usually is much richer than that in effect when the engine is operated at high speed and high power output.

The foregoing illustrates that fuel:air ratio - which depends upon carburetor design and adjustment - is the basic factor that determines the carbon monoxide content of the exhaust gases produced by a gasoline engine.

VOLUME OF EXHAUST GAS

To base an estimate of ventilation requirements upon production of carbon monoxide by an engine, information must be available on both the percentage of this gas in the exhaust and the rate at which exhaust gas is produced.

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The volume of exhaust gas produced per pound of gasoline burned in an engine varies with fuel:air ratio and may be calculated from a material balance between fuel and exhaust gas. The following relation, based upon the carbon content of the gasoline and of the exhaust gas, is suitable for such calculation:

$$V = \frac{379.4C}{12.01\ (CO_2 + CO + CH_4 - 0.03)} \qquad (1)$$

in which

V = volume of exhaust gas produced per pound of gasoline, cubic feet at 60° F. and 29.92 inches of mercury pressure.

379.4 = mol volume = cubic feet of dry gas (at 60° F. and 29.92 inches of mercury) equivalent to one pound-molecule of the gas in question.

C = percent, by weight, of carbon in the gasoline.

12.01 = molecular weight of carbon.

$CO_2 + CO + CH_4$ = sum of percentages, by volume, of carbon-containing gases in the exhaust.

0.03 = carbon dioxide content of normal air, percent by volume.

For a gasoline containing 85 percent carbon,9/ the expression reduces to

$$V = \frac{2685}{(CO_2 + CO + CH_4 - 0.03)} \qquad (2)$$

Table 2 contains data on volume of exhaust gas and carbon monoxide produced per pound of gasoline at different fuel:air ratios, based upon equation (2) and the average analyses given in table 1. The same data are shown graphically in figure 2.

TABLE 2. - Volume of exhaust gas and of carbon monoxide produced per pound of gasoline at different fuel:air ratios

Fuel:air ratio, pound of fuel per pound of air	Volume of exhaust gas produced per pound of fuel, cu. ft.1/	Carbon monoxide content of exhaust gas, percent by volume	Volume of carbon monoxide produced per pound of fuel, cu. ft.1/
0.05	256	0.05	0.13
.06	209	.20	.42
.07	177	1.74	3.1
.08	165	5.16	8.5
.09	152	8.50	12.9
.10	146	11.00	16.1
.11	140	12.95	18.1

1/ Dry gas at 60° F. and 29.92 inches of mercury pressure.

9/ An approximation of the carbon content of the average gasoline; minor variations from this value do not affect the calculation significantly.

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RATE OF PRODUCTION OF CARBON MONOXIDE

The three factors involved in computation of the rate at which carbon monoxide is produced by a gasoline engine are

(1) Carbon monoxide content of the exhaust gas,

(2) Volume of exhaust gas produced per pound of fuel, and,

(3) Rate of fuel consumption by the engine.

Items 1 and 2 may be calculated from the composition of the exhaust gas and of the fuel, and item 3 must be measured for the engine in question under typical operating conditions.

Complete analysis of the exhaust gas would be desirable in calculating items 1 and 2, but in many instances a simpler analytical procedure will suffice.

As shown in figure 1, there is a definite relationship between the carbon dioxide content of the exhaust, the fuel:air ratio at which the engine is operating, and the carbon monoxide content of the exhaust. It is evident, therefore, that if the carbon dioxide content of the exhaust is known, this information will serve as an index of the other factors involved in estimating the rate at which carbon monoxide is produced. The oxygen content of the exhaust should be determined as well as the carbon dioxide content, as it may be noted from figure 1 that, within a certain range of fuel:air ratios, like values for carbon dioxide exist on both sides of the chemically correct fuel:air ratio, and that knowledge of the oxygen content serves to indicate, in such instance, whether the fuel:air ratio is on the lean or the rich side of the chemically correct ratio.

Any of the types of gas-analysis apparatus commonly used for flue-gas analysis is suitable for determining the carbon dioxide and oxygen contents of the exhaust gas for the purpose of estimating ventilation requirements. Samples of the exhaust gas should be collected,[10/] and measurement of rate of fuel consumption should be made at different conditions of engine operation to furnish information representative of over-all performance. To be on the safe side, the operating condition that indicates the highest rate of carbon monoxide production should be the condition upon which the ventilation estimate is based.

ESTIMATION OF REQUIRED VENTILATION

When information has been obtained on the rate at which carbon monoxide is produced, the rate at which ventilating air must be supplied to dilute the carbon monoxide to an acceptable level - say, 0.01 percent by volume[11/] - in the general atmosphere of an enclosure may be calculated from the following relation:

10/ In sampling the exhaust gases of an internal-combustion engine, care must be exercised that the sample is not contaminated with air. Because of the pulsating nature of the exhaust, the sampling point should be as close as possible to the engine. A metal tube inserted well into the exhaust pipe or muffler tail pipe provides a means of collecting uncontaminated samples.

11/ The concentration generally considered the maximum permissible in the air of working places for exposures not exceeding 8 hours daily.

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$$V_a = \frac{V_{co} \times 100}{0.01} \times R \qquad (3)$$

in which

V_a = volume of ventilating air required, cubic feet (at 60° F., and 29.92 inches pressure) per hour.

V_{co} = volume of carbon monoxide produced per pound of gasoline burned, cubic feet at 60° F., and 29.92 inches pressure.

R = rate of gasoline consumption by the engine, pounds per hour.

Data previously presented have been combined in figure 3 to illustrate the procedure for estimating ventilation requirements. For example, assume that the exhaust gas has been analyzed and has been found to contain 10.8 percent by volume of carbon dioxide and 0.3 percent oxygen (the low oxygen content indicating that the fuel:air mixture is on the rich side), and that 1 gallon of gasoline (approximately 6 pounds) is used by the engine in 1 hour under typical operating conditions. Then, by following the dotted lines in figure 3, it is seen that fuel:air ratio is 0.08, the carbon monoxide content of the exhaust is 5.2 percent, 8.5 cubic feet of carbon monoxide are produced per pound of gasoline consumed, and 85,000 cubic feet of air are required to dilute to 0.01 percent the carbon monoxide produced per pound of gasoline. As 6 pounds of gasoline are consumed by the engine per hour, the rate of ventilation should be 85,000 x 6, or 510,000 cubic feet per hour, or 8,500 cubic feet per minute.

The estimation of ventilation requirement is based upon reduction of the carbon monoxide content of the general atmosphere to a certain average value, assuming that distribution of air and exhaust gas is uniform throughout the enclosed space. Actually, the concentration of exhaust gas and of carbon monoxide in the immediate vicinity of the engine exhaust is always higher than the average. It is evident, therefore, that any means that can be used to accelerate mixing of the exhaust gases with the surrounding air will be beneficial. The manner in which the exhaust gases are discharged from the vehicle and the manner in which the ventilating air traverses the enclosure are factors that influence the dispersion of the gases.

From studies of ventilation in garages[12], [13] it appears that in one-story buildings the most advantageous results are obtained by admission of fresh air at floor level with exhaust near the ceiling or roof. In multiple-storied buildings with interconnecting floors, cross ventilation for each story seems advisable.

12/ Houghten, F. C., and McDermott, P., Carbon Monoxide Distribution in Relation to the Ventilation of a One-Floor Garage: Heating, Piping, and Air-Conditioning, vol. 4, 1932, pp. 495-501.

13/ Houghten, F. C., and McDermott, P., Carbon Monoxide Distribution in Relation to the Ventilation of an Underground Ramp Garage: Heating, Piping, and Air-Conditioning, vol. 4, 1932, pp. 559-571.

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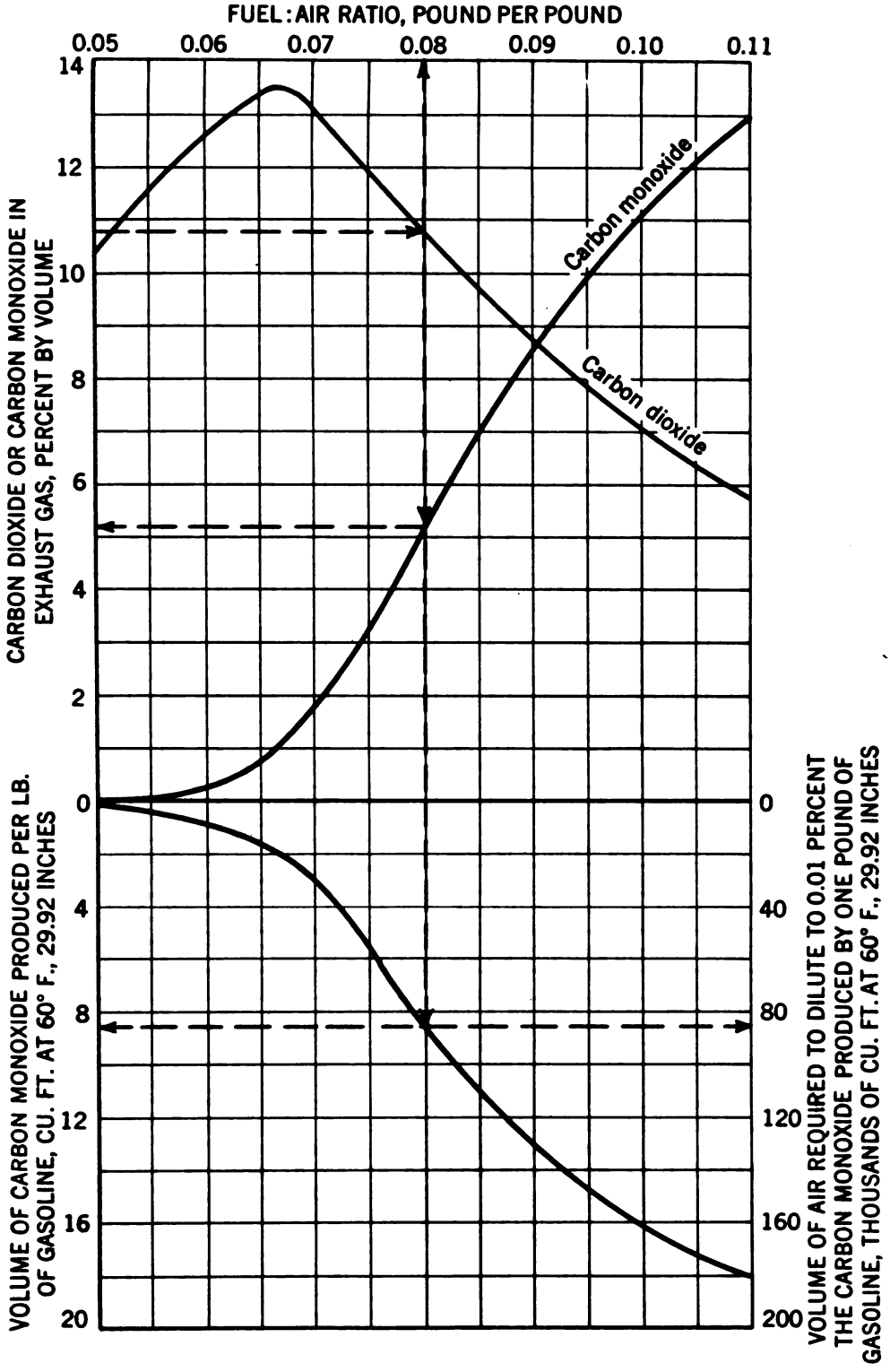

Figure 3.—Relation between exhaust gas composition, fuel : air ratio, production of carbon monoxide, and ventilation required.

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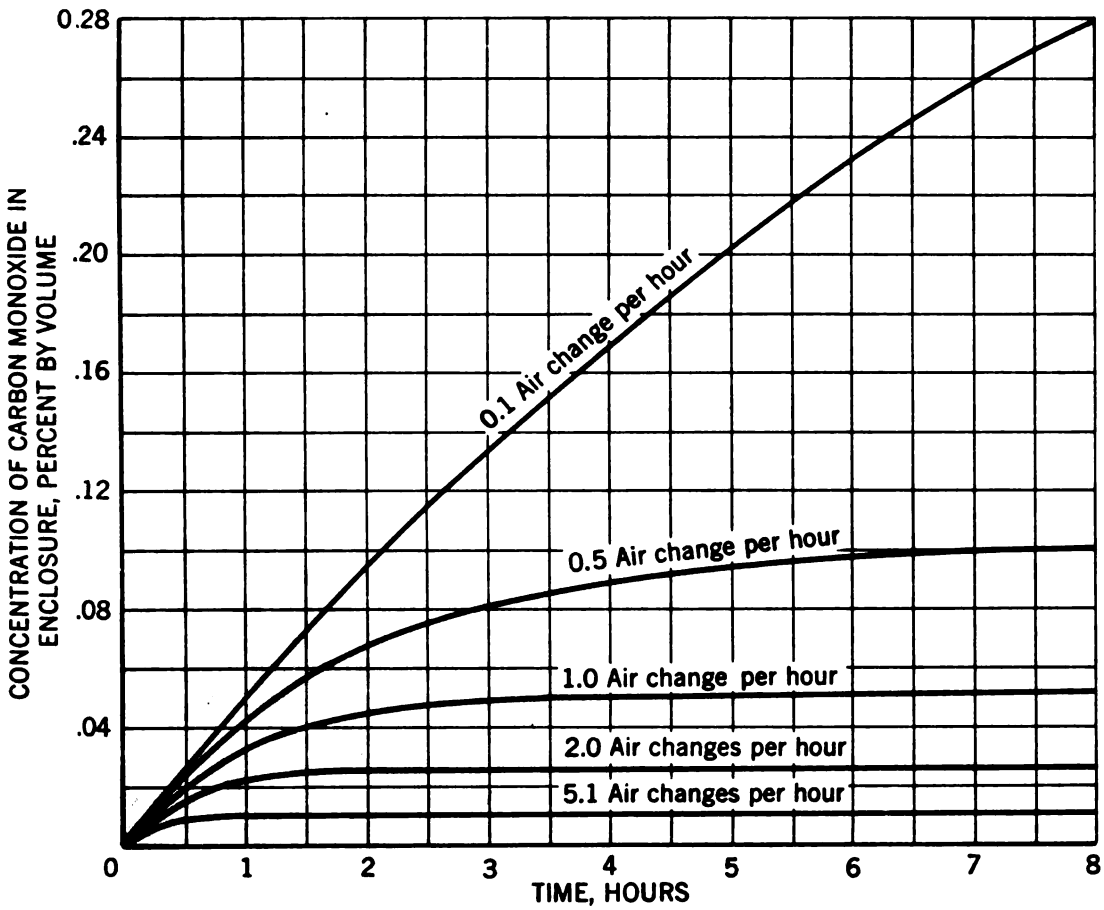

Figure 4.—Average concentrations of carbon monoxide produced during an 8-hour interval, and with different rates of air-change, in an enclosure of 100,000 cubic foot volume in which carbon monoxide is liberated at the rate of 51 cubic feet per hour.

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When the rate of production of carbon monoxide and the rate of air-change in a space of given size are known, the average concentration of carbon monoxide existing in the space after a given time interval may be calculated from the relation[14]/

$$C = \frac{100K}{RV_s}(1 - e^{-Rt}) \qquad (4)$$

in which

C = average concentration of carbon monoxide in the space after a given time, percent by volume.

R = air-changes per hour.

t = time in hours.

V_s = volume of space, cubic feet.

K = rate of carbon monoxide liberation in space, cubic feet per hour.

e = base of natural logarithms = 2.718.

Equation (4) was applied in preparing figure 4, showing the rate of increase of the average carbon monoxide concentration in a space of 100,000 cubic feet, with different rates of air change and with the production of carbon monoxide the same as that assumed in a previous example (8.5 cubic feet of carbon monoxide produced per pound of gasoline and 6 pounds of gasoline consumed per hour,[15]/ or 51 cubic feet of carbon monoxide liberated in the space each hour).

From figure 4 it is seen that with the lowest rate of air-change shown, the average concentration of carbon monoxide would continue to increase throughout an 8-hour period and would exceed 0.01 percent within 1/4 hour. As rate of air change is increased, equilibrium in concentration is approached in progressively shorter times, and only at the rate of air change calculated from equation (3) (510,000 cubic feet per hour, or an air-change rate of 5.1 per hour in a space of 100,000 cubic feet) is the average concentration of carbon monoxide held to the permissible level of 0.01 percent.

As the curves shown in figure 4 represent the average concentrations of carbon monoxide in the space, the figure illustrates that even with adequate ventilation attention must be given to distribution of ventilation in the space to approach uniformity in the general atmosphere and to reduce the concentration

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14/ Jones, G. W., Berger, L. B., and Holbrook, W. F., Carbon Monoxide Hazards from House Heaters Burning Natural Gas: Bureau of Mines Tech. Paper 337, 1923, 30 pp.

15/ This rate of fuel consumption is equivalent to a continuous power output of 12 horsepower from a gasoline engine, if it is assumed that the specific fuel consumption (lb. of fuel/Hp./hr.) of such engines is 0.5.

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of carbon monoxide to the desired level. Adequate protection should also be maintained against occurrence of fire and in fire fighting, should one occur.

SUMMARY

1. The purpose of this paper is to present data that may be used in estimating the rate of ventilation required in enclosed spaces where a hazard from carbon monoxide may be created by the use of mobile equipment powered by gasoline engines. Under no circumstances should gasoline-powered equipment be used in mines or tunnels.

2. Data are presented showing the relationship of concentration of carbon monoxide and of other constituents of the exhaust gas to the proportions of fuel and air in the mixture supplied to the engine by the carburetting device. Fuel:air ratio is therefore the basic factor that determines the concentration of carbon monoxide in the exhaust gas of a gasoline engine.

3. The volume of exhaust gas produced per unit weight of fuel burned in the engine is related to fuel:air ratio and may be calculated from data on composition of the exhaust gas and of the fuel.

4. The rate at which carbon monoxide is produced is the factor upon which ventilation estimates are based, and this factor may be calculated from data on rate of fuel consumption, volume of exhaust gas per unit weight of fuel, and concentration of carbon monoxide in the exhaust gas.

5. An example is given of the method of estimating rate of ventilation required under given conditions, and the effect of air-change rate upon concentration of carbon monoxide in a typical enclosure is illustrated.

6. It is pointed out that to insure adequate ventilation, attention must be given to the manner in which the ventilating air is distributed throughout the enclosure.

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